DTU Library

Risk assessment of wind turbines close to highways

Sørensen, John Dalsgaard; Sørensen, Jens Nørkær; Lemming, Jørgen Kjærgaard

Published in:
Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Risk assessment of wind turbines close to highways

John Dalsgaard Sørensen[1,2], Jens Nørkær Sørensen[2] and Jørgen Lemming[2]
jds@civil.aau.dk; jnso@mek.dtu.dk; jqle@dtu.dk
1) Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark
2) DTU Wind Energy, Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark

Summary

This paper describes an assessment of the minimum distance from wind turbines to highways based on risk assessments of the consequences due to total or partial failure of a wind turbine and due to ice throw in case of over-icing. Data has been collected from a large number of modern wind turbines from Denmark and abroad and with the same basic technology as new large wind turbines. These data contain information on events where parts of the turbine is thrown / dropped at a distance from the turbine.

Based on the data, the risk is estimated that persons in car are killed because of wind turbine parts 'thrown away' from a wind turbine in events with total or partial failure. The risk is expressed as a probability per kilometer. It is assumed that a row of wind turbines is placed along a highway with a typical total height of 120m (equivalent to wind turbines in the underlying data base) and a spacing of 400-500 m along the road.

The studies show that the probability per kilometer that a person in a vehicle is killed due to total or partial collapse (damage) of a wind turbine can be assumed to be of minor importance. The probability per kilometer will be less than 5 10^{-12} for wind turbines that are more than 60 meters from the road. This risk is considered acceptable using the ALARP principle and comparing with the general, well-documented risk on roads in Denmark which in 2009 was 2 10^{-9}. The analysis also shows that the height of the turbines and the distance between them is of less importance.

Assessment of risks due to ice throw in case of over-icing is also performed. This is associated with many uncertainties which are described and quantified in the paper mainly for Danish conditions. The assessment includes both situations where the turbine is in operation and situations where the turbine is stopped.

Both for pieces from the wind turbine and for ice the throwing distances are determined from ballistic computations assuming an average drag coefficient of 0.6. This number is based on results from a more elaborate model that takes into account the full 6 degrees of freedom movement of the fragments subject to detailed aerodynamic lift and drag forces.

The probability per kilometer that a person in a vehicle is killed due to ice throw from a wind turbine is determined and shown in the paper for tip heights at 150m as a function of distance to a number of wind turbines located along a highway with a spacing of 400m. As an example the generally accepted risk on highways in increased with less than 0.1% in wind turbines are installed more than 150 meters from the highway. The risk due to ice throw from a wind turbine in operation is seen to be slightly greater than the risk if the wind turbine is parked.

It is recommended that for practical projects a proper risk assessment is performed, which also include the location in relation to the road and the prevailing wind direction.

Introduction

Assessment of risks due to items thrown from wind turbines is important in connection with planning and installation of wind turbines near highways in Denmark and many other countries. This paper only considers risks due to falling parts from wind turbines in case of total or partial damage, and from ice thrown from wind turbines in case of icing.

Risk assessment in connection with wind turbine failures

The basis for calculating the probability that a vehicle on a road is hit by wind turbine parts thrown from wind turbines in case of total or partial failure is the following data from representative databases with failure data for modern wind turbines:

- Distance from the wind turbine
- Size of wind turbine part

Based on these data the probability P_Z per year per m^2 that an item thrown from a wind turbine hits in the area ΔA_j in between the radius R_{j-1} and the radius R_j from the wind turbine can be estimated:

$$P_{Z,j} = \frac{n_j}{\Delta A_j \cdot N_T} \tag{1}$$

where

n_j number of wind turbine parts between the radius R_{j-1} and the radius R_j

ΔA_j area between the radius R_{j-1} and the radius R_j

N_T number of years with data

The probability (per km) that a vehicle is hit by a wind turbine part thrown from a wind turbine located at a distance d from a road is estimated using the following model from [1]:

$$P_A = \frac{1}{V_0} \frac{1}{365 \cdot 24 \cdot 3600} \int_S P_Z(s) A(s) ds \cdot \frac{1}{D} \tag{2}$$

where

V_0 speed of the vehicle - is chosen to 80 km/h = 22 m/s for highways

$P_Z(s)$ probability determined from (1) as a function of the distance from the turbine

$A(s)$ area of the wind turbine part as a function of the distance

S road section considered

D spacing between wind turbines placed along a road

The statistical uncertainty associated with a limited number of failure data is included by using an upper 95% probability limit assuming that the failure events follows a Poisson process. Further, it is assumed that the consequence is that on average 1.5 people are killed if a wind turbine part hits a vehicle. The risk, R_A per kilometer to be killed by wind turbine parts thrown from wind turbines in case of failure is thus estimated from:

$$R_A = 1{,}5 \cdot P_D \cdot P_A \tag{3}$$

where it conservatively is assumed that the probability of being killed when an object hits a vehicle is P_D = 1.

Data has been collected from a large number of 'modern' wind turbines (from Denmark and abroad and with the same basic technology as new wind turbines). These data provide information on events, where parts from the turbine is thrown / dropped at a distance from the turbine. This covers items lost from the nacelle and parts thrown from the wind turbine blades and nacelle. The data contains information about the distance from the turbine where wind turbine parts lands and the size of the parts. Based on these data it is possible to determine the probability $P_Z(s)$ as a function of distance from the turbine and also the area $A(s)$ of the wind turbine parts. Next R_A can be determined as a function of the distance from a road. Figure 1 shows R_A for D = 400m and 500m.

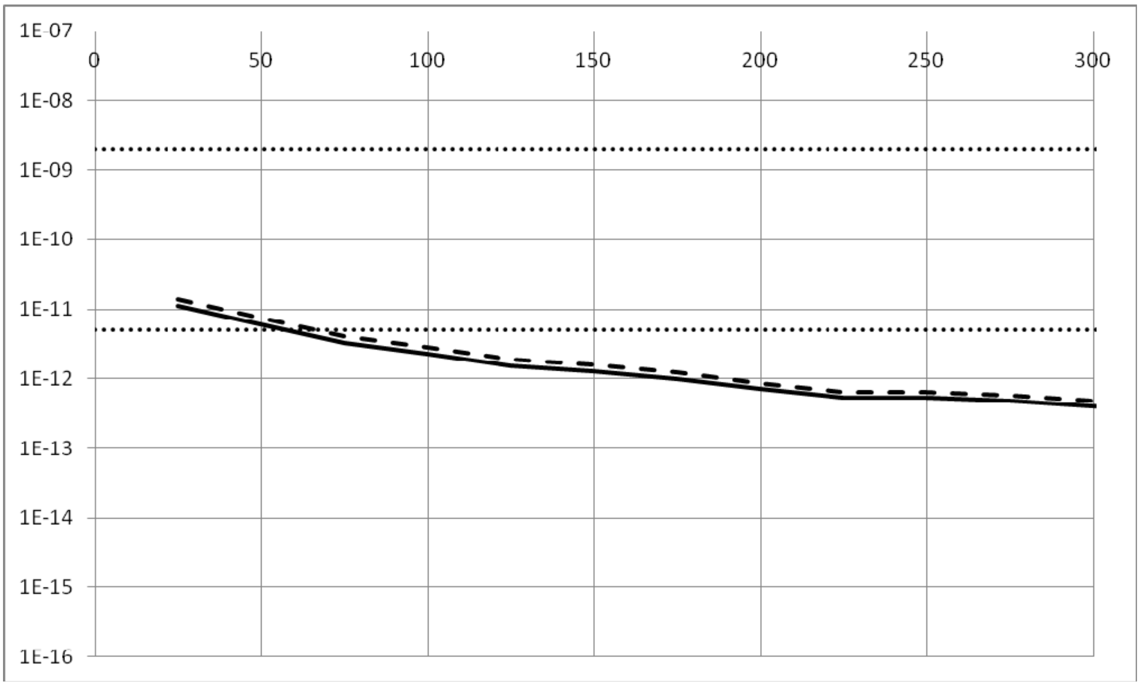

Figure 1 Probability per kilometer that a person in a vehicle is killed due to total or partial failure / collapse of a wind turbine as a function of distance to a road (in m). Solid line: D = 500m; dashed line: D = 400m; dotted lines show the probability levels 5 10^{-12} and 2 10^{-9}.

Figure 1 shows that the risk contribution of 'discarded' wind turbine parts can be assumed to be of minor importance (less than 5 10^{-12}) for turbines that are more than approx. 60 meters from the road when compared to the statistical risk of losing the life in general on highways, which is 2 10^{-9} per kilometer (2009), see [2]. In addition, the height of the wind turbines and the distance between them are also of minor importance.
In risk assessment the probability of being killed in the traffic can be expressed as per vehicle kilometer. A major reason for this is that there are well-documented data on this risk on highways in many countries including Denmark. In 2009 this probability was 2 10^{-9} per kilometer, see [2]. Using this so-called ALARP (As Low As Reasonably Practicable) principle, see [3] and [4] it is often assumed that an additional / extra risk contribution can be considered negligible if this contribution is less than the probability reduced by a factor of 100, i.e. 2 10^{-11} per kilometer. If future reduction of the overall risk level at the Danish highways is taken into account the acceptance limit can be reduced to 5 10^{-12} per kilometer.
It is noted that the above risk assessment is based on a large statistical data base for modern wind turbines. Previous risk assessments in connection with wind turbine parts thrown from failed turbines have been based on statistical information for the failure of older turbines, e.g. in [1], [5], [6], [7] and [8].

Risk assessment in connection with icing
The probability (per km) that a vehicle in connection with icing is hit by ice pieces thrown from a wind turbine located at a distance from a road is estimated using the following model based on (2):

$$P_A = \sum_{v_i = 5,10,15,20,25\text{m/s}} \left[\frac{1}{V_0} \frac{1}{365 \cdot 24 \cdot 3600} \int_S P_Z(s, v_i) A(s) ds \cdot \frac{1}{D} \right] \cdot P(V = v_i) \tag{4}$$

where

$P(V = v_i)$ probability that the mean wind speed at hub height in connection with icing is equal to v_i. The mean wind speed is discretized to the values of 5, 10, 15, 20 and 25 m / s

$P_Z(s,v_i)$ probability (per m per year) that an ice piece lands in the distance s from the turbine if the mean wind speed is v_i. A uniform probability distribution is assumed within the throwing distance R_i at the mean wind speed v_i. Furthermore, using a uniform directional distribution of the wind speed $P_Z(s,v_i)$ is determined by

$$P_Z(s,v_i) = \nu \frac{1}{R_i} \tag{5}$$

where ν is the number of icings per year.

Ice class	Thickness [mm]	Frequency [number per year]
1	<0,1	0,775
2	0,1-1,5	1,455
3	1,5-3	0,395
4	3-5	0,110
5	5-10	0,060
6	10-20	0,005

Table 1 Observed icings in Denmark, [9].

Table 1 shows the number of icings per year on average over 4 stations (Billund, Aalborg, Copenhagen, Skrydstrup) for different ice classes, based on observations from DMI over 50 years, [9]. The observations show that icing events rarely last more than 12 hours. The area $A(s)$ of a vehicle is chosen to 10 m^2 corresponding to the size of an ordinary passenger car.

It is estimated that ice pieces must have a minimum thickness of 2cm to be thrown over larger distances without going into smaller pieces and simultaneously could do damage to a passing vehicle. In the literature ice pieces at 1.0 to 1.5 kg is often used in the assessment of risks in connection with icing. It has not been possible to find data for ice throw from wind turbines in Denmark. The primarily reason is that icing has not been a problem for wind turbines under Danish climatic conditions.

Table 1 shows that in Denmark on average icing with ice thicknesses larger than 3mm occurs 0.175 times per year. This information is linked to icing of standing-still structures at the surface. As the ice thickness grows with the wind speed, larger ice pieces may be built up on rotating blades. Further, climatic situations at hub height may imply larger ice pieces than at the ground. Based on these considerations an approximate estimate is used of the frequency of icing ν = 0.175 times per year which may cause ice pieces that can be thrown over larger distances. It is noted that this estimate is highly uncertain.

In case of icing of the blades a number of pieces of ice could be thrown. It has not been possible to obtain data for this. Approximately it is assumed that in one icing up to 10 ice pieces with a weight of 1 kg can be thrown. It is noted that this estimate is subject to large uncertainty.

Wind speeds from DMI recorded in connection with icing (10m height) over a period of 50 years shows a mean value of 6.3 m/s and a standard deviation of 2.9 m/s if the wind speeds are converted to tip height (150m) for terrain category 2 (agricultural land) the probabilities in Table 2 are obtained for the discretized mean wind speeds. It should be noted that in (4) 10-minute mean wind speeds are used.

v_i	$P(V = v_i)$
5 m/s	0,27
10 m/s	0,45
15 m/s	0,17
20 m/s	0,04
25 m/s	0,004

Table 2 Probabilities for (10 minutes) mean wind speeds in tip height in connection with icing.

Throwing distances are determined by ballistic calculations based on the models described in [10] and [11]. In the ballistic calculations are used an average drag coefficient of 0.6, density of air at 1.3 kg/m^3 and of ice at 800 kg/m^3. The coordinate system is with the turbine placed at Origo, i.e. distances are calculated from the wind turbine (not from the ice location on the blades).
Throwing lengths during operation of the turbine is determined with a blade tip speed at 70 m/s, tower height = rotor diameter and ice thickness = 2cm. Tower heights correspond to the installed effects: 40m ~ 500kW, 50m ~ 700kW, 70m ~ 1.5MW, 2.5MW and 100m ~ 120m ~ 3.6MW. The results are shown in Tables 3 and 4 for the Psi = +45 degrees and Psi = -45 degrees. Psi is the angle between the horizon and the blade at tower height. I.e. at +psi the blade is in between tower and top, while at -psi it is in between its lower position and the tower height.

Tower height v_i	40 m	50 m	70m	100 m	120 m
5 m/s	69	69	67	70	68
10 m/s	88	91	98	111	121
15 m/s	112	119	134	159	178
20 m/s	138	149	172	209	234
25 m/s	166	181	212	259	292

Table 3. Throwing lengths (i m) during operation for Psi = +45 degrees.

Tower height v_i	40 m	50 m	70m	100 m	120 m
5 m/s	91	96	104	117	125
10 m/s	100	105	115	130	140
15 m/s	113	119	132	150	162
20 m/s	129	137	152	174	189
25 m/s	147	156	274	200	218

Table 4. Throwing lengths (i m) during operation for Psi = -45 degrees.

'Throwing lengths' for a stopped wind turbine is determined for various tip heights (total height) and an ice thickness = 2cm. The results are shown in Table 5.

Total height v_i	50 m	75 m	100 m	150 m	200 m
5 m/s	7	12	18	30	42
10 m/s	16	27	38	62	87
15 m/s	28	45	62	98	135
20 m/s	42	64	88	136	185
25 m/s	57	85	115	176	238

Table 5. Throwing lengths (in m) for a stopped wind turbine.

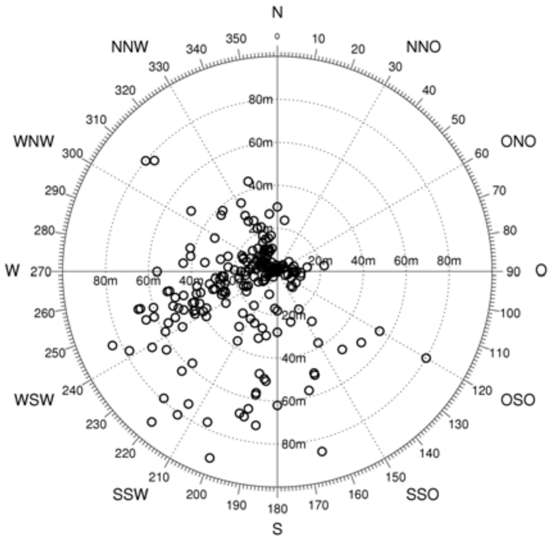

Figure 2 Observed ice pieces from Guetsch, [12].

Figure 2 shows the observed throwing lengths from a 600 kW Enercon E-40 wind turbine, [12]. These data broadly confirm the calculated throwing lengths for a stopped wind turbine. In table 5 the second column shows the throwing lengths for ice pieces for a stopped wind turbine with a tower height of 50m and a rotor radius 25m. This corresponds to a wind turbine at 6-700 kW, where a maximum throwing length at 25 m/s wind is estimated to 85 m. Figure 2 shows the corresponding maximum throwing length to be 92m. This gives an error of less than 10% in the calculation of the maximum throwing length.

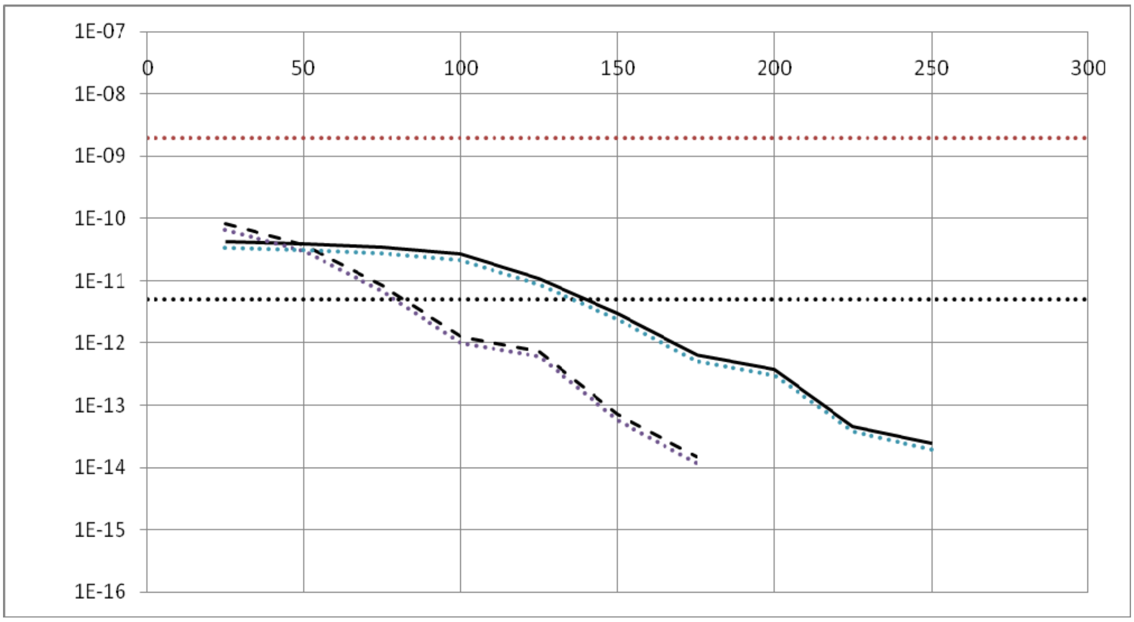

Figure 3. Probability per kilometer that a person in a vehicle is killed due to ice throw from a wind turbine as a function of the distance to a road. Tower height / total height = 100m / 150m. Solid curve: wind turbine in operation - dashed curve: wind turbine stopped: D = 400m; dotted line: D = 500m.

If it further is assumed that the consequence if an ice piece hits a vehicle is that in average 1.5 persons in 10% of the cases will be killed if a vehicle is hit, then the risk due to ice throw in case of icing is estimated to:

$$R_A = 1{,}5 \cdot N_{is} \cdot P_D \cdot P_A \tag{6}$$

where

P_D = 0.1 is the probability of being killed if an ice piece hits a vehicle

N_{is} = 10 is the number of 'big' pieces of ice, which are thrown in case of icing

In Figure 3 is shown for a for a wind turbine with a total height of 150m the probability per kilometer that a person in a vehicle is killed due to ice throw from a wind turbine as a function of the distance to a road, both for wind turbines in operation, and for turbines that are stopped. Conservatively, the maximum throwing lengths for Psi = + / -45 degrees was used.
In Figure 4 is shown for a for a wind turbine with a total height of 200m the probability per kilometer that a person in a vehicle is killed due to ice throw from a wind turbine as a function of the distance to a road, both for wind turbines in operation, and for turbines that are stopped.
From Figure 3 and 4 it is seen that the risk that a person is killed in a car in case of ice throw decreases significantly when the distance increases. The maximum throwing distance roughly corresponds to 1.7 times the wind turbine height.

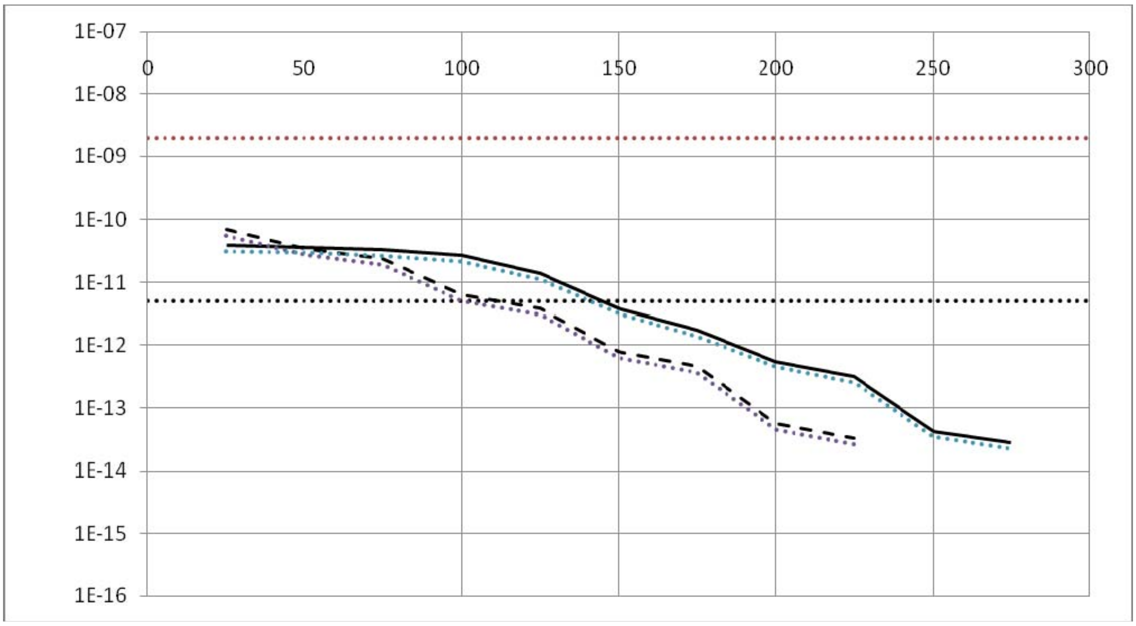

Figure 4 Probability per kilometer that a person in a vehicle is killed due to ice throw from a wind turbine as a function of distance to a road. Tower height / total height = 120m / 200m. Solid curve: wind turbine in operation - dashed curve: wind turbine stopped: D = 400m; dotted line: D = 500m.

The risk in connection with ice throw for a wind turbine in operation is seen to be slightly larger than the risk if the wind turbine is stopped. It is noted that pieces of ice during operation typically are thrown perpendicular to the wind direction, while for a stopped turbine they are typically thrown into the wind.
For icing of blades during operation the calculations do not include effects of the eventual heating of the blades in case of icing, that the wind turbine control system stops the blades in case of mass imbalance, that the blades can have special coatings that counteracts formation of ice and that wind turbines can be stopped if icing is forecasted.
As described above, there are a number of significant uncertainties in determining the level of the probability per. kilometer. It is therefore recommended that for practical projects a proper risk assessment is carried out, which also should include the location of the wind turbine in relation to a road and the prevailing wind direction.

Based on observations of ice throw Seifert [13] has suggested the following empirical model to determine a 'risk-circle' for ice throw from wind turbine blades for wind turbines in operation:

$$d = (D + H) \cdot 1.5 \tag{7}$$

where D is the rotor diameter and H is the hub height.
For a stopped wind turbine the following simplified empirical formula for the determination of maximum distance of ice throw is suggested in [13]:

$$d = V \frac{D/2 + H}{15} \tag{8}$$

where V is wind speed at hub height in m/s; D and H are in meters Based on this simplified model at a typical wind speed of 20 m/s a maximum distance of 1.7 times the turbine's total height is obtained. It noted that this model is not based on a risk analysis. For example, it would be appropriate to include the probability of different wind speeds in the assessment of the distance requirements for a stopped wind. Examples of more detailed analyzes are provided in [14] and [15], see also [16].

Table 6 shows the percentage increase in probability that a person in a vehicle is killed due to wind turbine parts and ice pieces thrown for different distances between the road and wind turbine. Comparison is made with the probability per kilometer equal to 2 10^{-9} (2009) as discussed above. It is seen that the increase in risk is very small for distances over 150m.

Distance [m]	Wind turbine parts	Ice throw – wind turbine in operation	Ice throw – wind turbine stopped
50	0,37	1,9	1,8
100	0,14	1,4	0,06
150	0,08	0,1	0,004
200	0,04	0,02	
250	0,03	0,001	
300	0,02		

Table 6 Increase (in percent) of the probability that a person in a car is killed due to wind turbine parts and ice pieces thrown for different distances between the road and wind turbine.

Acknowledgements
The authors gratefully acknowledge the financial support from the Danish Energy Agency.

References
1. Braam, H., G.J. van Mulekom & R.W. Smit: Handboek Risicozonering Windturbines. (Handbook Risk Assessment of Wind Turbines), Novem, 2005. (in Dutch).
2. Vejdirektoratet.dk, Interactive yearly statistics, http://webapp.vd.dk/uheldnykomm/UhRapport.asp?page=document&objno=105608 (June 5, 2011)
3. Health & Safety Executive, UK: The tolerability of risk from nuclear power stations. 1988, revised 1992. HMSO.
4. Melchers R.: On the ALARP approach to risk management. Reliability Engineering and System Safety. Vol. 71, No. 2, 2000, pp 201–208.
5. Braam, H. & L.W.M.M. Rademakers: Guidelines on the Environmental Risk of Wind Turbines in the Netherlands. Report ECN-RX--04-013, ECN, 2004.
6. Sørensen, J.D., J.N. Sørensen & P. Friis-Hansen: Risk assessment in connection with new wind turbines at Avedøre Holme, RISØ-DTU, April 2008 (in Danish).
7. Sørensen, J.D. &, J.N. Sørensen: Risk assessment in connection with new wind turbines at Kappel, RISØ-DTU, May 2009 (in Danish).

8. Garrad Hassan: Recommendations for risk assessment of ice throw and blade failure in Ontarrio. 2007.
9. Nielsen, N.W.: Note on icing at wind turbine blades. Danish Meteorological Institute, Marts 2011 (in Danish).
10. Sørensen, Jens N.: Beregning af risiko for personskade ved vindmøllehavari, hvor en vinge løsrives. Rapport AFM 83-07, Afdelingen for fluid mekanik, Den Polytekniske Læreanstalt, Lyngby, 1983 (in Danish).
11. Sørensen, J.N. 'On the calculation of trajectories for blades detached from horizontal axis wind turbines', Wind Engineering, vol. 8, no. 3, 1984.
12. Cattin, R., A. Heimo, S. Kunz, G. Russi, M. Russi, M. Tiefgraber, S. Schaffner, B.E. Nygaard: Alpine Test Site Guetsch - Meteorological measurements and wind turbine performance analysis. IWAIS XII, Yokohama, October 2007.
13. Seifert, H., A. Westerhellweg & J. Kröning: Risk analysis of ice throw from wind turbines. DEWI, 2003.
14. Morgan, C. & E. Bossanyi: Wind turbine icing and public safety - A quantifiable risk? Wind Energy Production in Cold Climates, 1996.
15. Boucetta, Y. & P. Heraud: Ice throw risk assessment for the proposed kingdom community wind power project. Garrad Hassan, 2010.
16. Laakso et al.: State-of-the-art of wind energy in cold climates. IEA R&D Wind, 2003.